NORD/LB

Hydrogen economy: Prospects, challenges and limits

Sector Strategy

7 July 2021

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Introduction: Climate change – Time for action

Alongside the current topic of COVID 19, climate change is undoubtedly one of the key issues of our time. The latter is of course not about climate change as such, but all about effective strategies and measures towards combatting it. The urgency for this is growing, as the IPCC[1] concluded in 2018 in a special report on global warming. This report found that CO2 emissions need to be reduced by 50 percent by 2030 so that global warming does not get out of hand and the targeted level of 1.5-percent determined under the Paris Agreement on climate change can be achieved.[2] The economic consequences of failing to do so would otherwise be simply too high, as the following assertions make clear:

- A study by the McKinsey Global Institute concludes that the alternative of taking no action would have significant socio-economic consequences worldwide.[3] According to the CRO Forum the physical risks alone would likely add up to USD 550 trillion by 2050.[4]
- Calculations by the Federal Reserve of Dallas arrive at the conclusion that failure to consistently and rigorously combat climate change would make for annual climate-related costs of just over 1.5 percent of gross domestic product (GDP) for the European Union in 2050. The figures for China and the USA in this context would be 1.6 and just short of 3.8 percent respectively, with a global average of 2.5 percent. Indeed, distinctly negative effects would already manifest themselves in 2030 and thus in the foreseeable future. For the European Union this would entail a minus 0.5 of percent in GDP.[5]

Alone the prevention of these adverse effects – which, moreover, would also impact the living conditions of large numbers of people correspondingly – is reason enough for measures to be taken towards tackling climate change. Investments in climate protection would also result in positive effects as well. A study by ATKearney suggests that these could lead to a plus of USD 15 trillion in global GDP as against the status quo, the prerequisite for this being, however, a basis of international cooperation in the pursuit of climate protection objectives. [6]

Against this background the European Union and Germany have defined corresponding CO2 targets:

- In December 2020 the EU reached an agreement on ramping up its climate protection targets, providing for a reduction of at least 55 percent in greenhouse gas emissions by 2030 compared to 1990, and the achievement of climate neutrality by 2050.
- By way of its Climate Protection Act, Germany has so far targeted a reduction of 55 percent (as against 1990) in greenhouse gas emissions by 2030, with individual targets being set for the sectors of energy, industry, buildings, transport, agriculture and waste compared to reference year 1990. Germany's Agora Energiewende[7] think tank anticipates a new target of 65 percent in the wake of the EU's ramping up of objectives. Germany, too, is aiming for complete climate neutrality by 2050. The following chart shows what this could mean for the individual sectors.

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[1]IPCC = Intergovernmental Panel on Climate Change
[2]IPCC: Global Warming of 1.5ºC – An IPCC Special Report on the impacts of global warming of 1.5º above pre-industrial levels and related global greenhouse gas emissions pathways, 2018
[3]McKinsey Global Institute: Climate risk and response – Physical hazards and socioeconomic impacts, 2020
[4]CRO-Forum: The heat is on – Insurability and Resilience in a Changing Climate, Emerging Risk Initiative Position Paper, 2019
[5]Federal Reserve Bank of Dallas: Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis, Global Institute Working Paper 365, 2019
[6]ATKearney: The economic costs of climate change: Lessons learned from COVID-19, Council perspective 2021
[7]Agora Energiewende, Stiftung2º, Roland Berger: Climate neutrality 2050: What industry needs from politics now, 2021

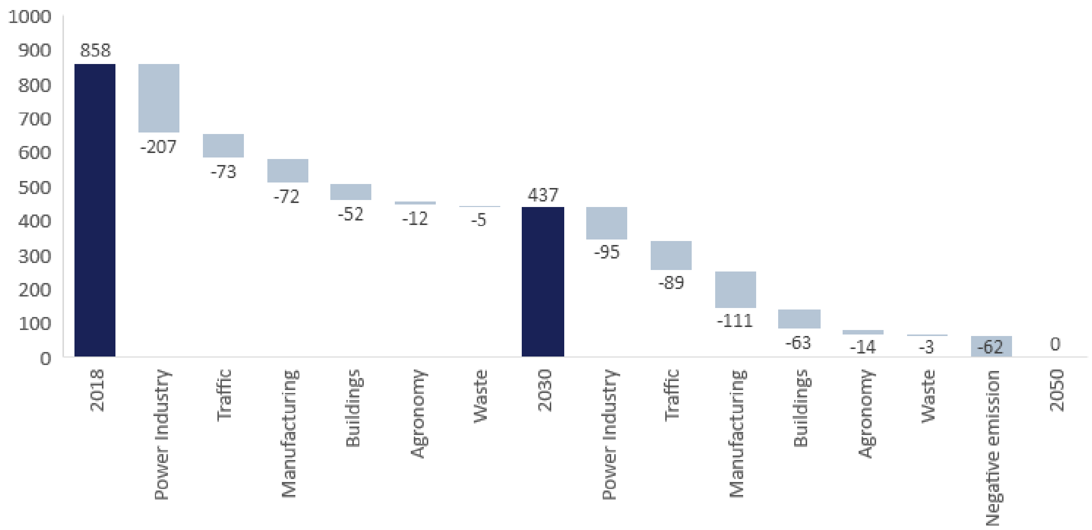
Similar targets have in the meantime been announced in an international context as well. China, for example, intends to become climate-neutral before 2060 while the US aims to have done so by 2050 after the change of government.

Given these targets and objectives, the question arises as to the current situation regarding CO2 emissions. And the regrettable fact is that there still remains a great deal to be done, at least in the global context, as reflected by the following figures:[8]

- 2019, saw global CO2 emissions hit a peak of 36.4bn tonnes of CO2. The corona pandemic will have led to a decline of 5.8 percent in 2020, though this is only attributable to the sharp downward trend in the first half of the year. Indeed, CO2 emissions were actually up again towards the end of year in December by 2.0 percent in year-on-year comparison. This indicates what is merely a one-off special effect and the absence of a planned structural decline in emissions.
- With a figure of 1.9 percent, Germany accounts for a comparatively small share. In absolute figures, 810m tonnes of CO2 were emitted in 2019, meaning a decrease of 35.1 percent compared to 1990 and, at the same time, documenting the necessary savings on emissions to be made by 2030. The corona pandemic benefited the situation in 2020, with CO2 emissions down to 739m tonnes.[9]

Against this background it becomes clear that there are still considerable challenges ahead of us worldwide, but also in Germany, which need to be solved in order to achieve the ultimate objective of climate neutrality. The following chart shows a possible development path for Germany.

Measures towards achieving climate neutrality in 2050 (figures in million t CO2-equ.)



Sources: Agora Energiewende 2020, NORD/LB Sector Strategy

A technology increasingly discussed and fostered for some time in the context of the required solutions (including electrification, coal phase-out, etc.) is that of hydrogen. Against this background, this study sets out to shed more light on the prospects offered by hydrogen and the challenges and limits associated with it.

[8] Cf. IEA
[9] Federal Environment Agency

Why is hydrogen a key building block in the quest for climate neutrality?

Hydrogen is already being used

The production and use of hydrogen is not new. On the contrary, it is a long-known technology and hydrogen plays a key building block in various industrial production processes. The most important fields of application in this regard are:[10]

- The synthesis of ammonia and methanol in the chemical industry as basis for the production of fertilizers and base materials. This accounts for around 40% of global annual hydrogen consumption.
- Use in steel production. The consumption here equates to approx. 3 percent of the annual global consumption volume.
- The processing and upgrading of hydrocarbons in the production of diesel and petrol fuels in refineries. This accounts for around 33 percent of the annual global hydrogen consumption.

The hydrogen required for these purposes either comes into being as a by-product in various processes or is predominantly obtained from fossil fuels (natural gas and coal).[11] Global hydrogen production is therefore currently responsible for approx. 830m tonnes of CO2.[12] According to the Federal Ministry of Economics, around 55 TWh of hydrogen are currently being produced from natural gas in Germany.[13]

This means that there is application potential for hydrogen in industry and thus also for the use of green hydrogen based on renewable energies. Substituting the previous industrial hydrogen consumption with green hydrogen would lead to a reduction of approx. 100 million tonnes in CO2 emissions per year in the EU.[14] This is also an important aspect for Germany since its industrial sector as a whole was responsible for 23.1 percent of the country's greenhouse gas emissions in 2019[15]. However, the sectors mentioned above only account for a part of these emissions.

Types of hydrogen depending on their form of production

In light of the above information, the question arises, on the one hand, as to the types of hydrogen. It should be noted that, while a primary energy source, hydrogen is a chemical element and not found in free form in nature. It must therefore be obtained through the conversion of other energy sources. In principle, the following variants can be distinguished with which specific CO2 emissions are associated:[16]

- Fossil-based hydrogen: hydrogen for the production of which fossil fuels are used as feedstock. When produced via coal gasification one speaks of brown hydrogen and of grey hydrogen when natural gas reformation is used. These two processes account for the bulk of hydrogen produced today and are characterized by high levels of greenhouse gas emission.

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[10]Fraunhofer: A hydrogen roadmap for Germany, 2019; IEA: The Future of Hydrogen - Seizing today's opportunities, 2019; ENCON.Europe, Ludwig-Bölkow-Systemtechnik: Potential atlas for hydrogen, 2018
[11]According to the IEA, 85.1 percent of hydrogen production worldwide comes from the conversion of fossil fuels and 14.9 percent from by-products.
[12]IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[13]BMWi: Dialogue Process Gas 2030 - Initial Stock-Take, 2019
[14]McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution No. 08/2021, April 2021
[15]Cf. Federal Environment Agency
[16]European Commission: A hydrogen strategy for a climate-neutral Europe, 2020

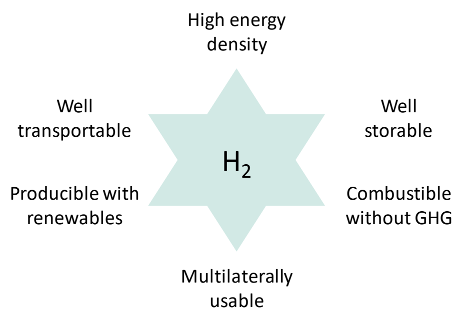
- Fossil-based hydrogen with CO2 capture: The CO2 emissions arising during production are captured and usually stored underground or possibly put to use. This form of hydrogen is known as blue hydrogen and is characterized by lower emissions as result of CCS[17].
- Electricity-based hydrogen: This type of hydrogen comes into being through the electrolysis of water. Depending on from which source the electricity is generated, a distinction is made between turquoise hydrogen (pyrolysis on the basis of natural gas), yellow hydrogen (use of electrical energy of mixed origin obtained from the grid) and hydrogen based on nuclear energy.
- White hydrogen: This form of hydrogen comes into being as a by-product of chemical processes and is not used as material but thermally utilized in the vicinity of its point of origin.
- Renewable or green hydrogen: Hydrogen produced through the electrolysis of water using renewable energies. The use of renewables means that greenhouse gas emissions tend towards zero. Green hydrogen can also be produced through biogas reformation or the biochemical conversion of biomass.

In light of the aforementioned climate protection targets and objectives it is immediately understandable and logical that green hydrogen in particular is a focus of interest. Alone the replacement of brown and grey hydrogen in industrial applications promises a significant reduction in CO2 emissions. Accordingly, green hydrogen is also core element of the hydrogen strategies pursued by the EU, Germany and the respective federal states.
At most blue or turquoise hydrogen are, with costs in mind, still being allowed a role as bridging technology. The extent to which this perspective is a realistic one remains to be seen. First, the social acceptance of the underground storage of CO2 is to be viewed rather critically and, second, both technologies can develop into "stranded assets" against the background of growing competitiveness from green hydrogen.

What characteristics make hydrogen interesting?

A variety of applications for green hydrogen are being discussed. These will be looked into in the following sections and go beyond the replacement of brown and grey hydrogen. Various positive characteristics associated with (green) hydrogen are responsible for this.

Chart: Positive characteristics of hydrogen



Sources: Energieinfo, GermanHy, NORD/LB Sector Strategy

Reference was already made in the above to the one of the positive characteristics. Hydrogen can and, also in the context of the energy transition, must be produced with renewables and thus climate-neutrally. Moreover, the combustion of hydrogen merely produces water vapour but no climate-damaging greenhouse gas emissions.

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[17]CCS = Carbon Dioxide Capture and Storage

In the following a look at the other characteristics:[18]

- Hydrogen has a higher gravimetric energy density than other chemical fuels. Compared to liquid fossil fuels, this is higher by a factor of 3.
- Hydrogen can be stored in larger amounts over longer periods of time, although the aspect of its low volumetric energy density needs to be taken into account. Salt caverns, which are used in Germany to store natural gas reserves, among other things, are particularly suitable for this purpose. Hydrogen is therefore suitable for compensating short-term and seasonal fluctuations in the production of renewables. This is important not least where ensuring security of supply for industrial processes is concerned. However, it should also be noted at this point that battery systems are currently more efficient and cost-effective than hydrogen for a short-term storage of renewables.[19]
- Hydrogen is transportable. Here, too, the low volumetric density aspect must be taken into account, meaning that hydrogen has to be processed (e.g. conversion into ammonia, liquefaction or gaseous compression[20]). This aspect is of twofold importance in climate change terms, however. On the one hand, the hydrogen has to be transported in Germany from its place of origin to the place of use. On the other hand, it can be assumed that an international producer and transport network needs to be created and established in order to ensure the ready availability of sufficient green hydrogen as substitute for fossil fuels. We will be addressing this aspect in the further course of the study.
- (Green) hydrogen is versatile in its uses, even if conversion processes will be necessary for these purposes. It can, for example, be used as a complementary fuel in the heating and mobility sector, as heat supplier for private households, trade and industry, or as feedstock in the chemical industry.[21] This characteristic will be presented in detail and justified in the respective application areas – also its suitability for sector coupling and thus its role towards achieving climate neutrality.

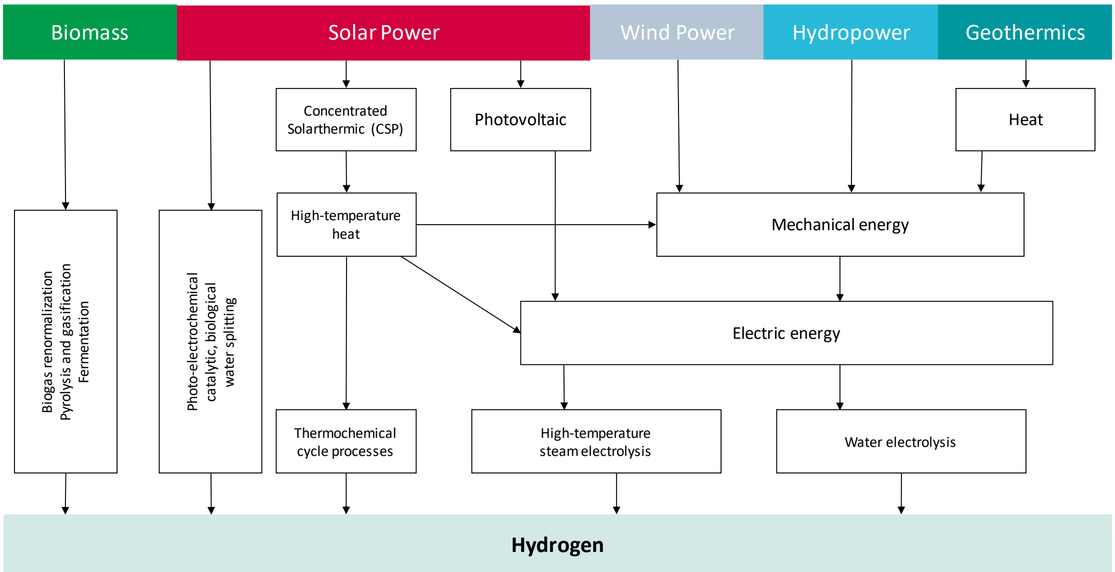
Initial notes on the potential limits of a hydrogen economy

An interim conclusion can be presented at this point to the effect that it is essentially only green hydrogen and a hydrogen economy based thereon that come into question where achieving the climate protection objectives is concerned. This also requires the adequate availability of renewables. To give an initial indication, these would have to be in sufficient supply to replace the 70m tonnes of hydrogen produced annually from fossil fuels worldwide.[22] In Germany, therefore, a volume of 57 TWh of produced hydrogen (2020 figure)[23] would have to be switched to renewable energy sources.

If we also include the potential areas of application in other sectors, the demand would be even higher. There basically exist various paths of hydrogen production towards satisfying such demand, which – without going into them in more technological detail[24] – are depicted in the following chart.

[18] DLR: Hydrogen as a foundation for the energy transition, Part 1: Technologies and perspectives for a sustainable and economical hydrogen supply, 2020
[19] McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution No. 08/2021, April 2021
[20] DLR: Hydrogen as a foundation for the energy transition, Part 1: Technologies and perspectives for a sustainable and economical hydrogen supply, 2020
[21] DLR: Hydrogen as a foundation for the energy transition, Part 1: Technologies and perspectives for a sustainable and economical hydrogen supply, 2020
[22] IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[23] Source: Statista
[24] As regards the technical side of the paths, reference is made to the DLR study. DLR: Hydrogen as a foundation for the energy transition, Part 1: Technologies and perspectives for a sustainable and economical hydrogen supply, 2020

Chart: Paths of hydrogen production from renewable energies



Sources: DLR, NORD/LB Sector Strategy

It can thus be concluded that the possibilities for the production of green hydrogen exist. That said, there are already some critical aspects to be noted at this point which must be taken into account in the building up and establishment of a sustainable hydrogen economy: [25]

- The hydrogen economy faces competition from other areas of application for renewables, for instance the direct use of electricity in mobility or in the buildings sector, etc. The majority of experts take the view that this will result in the necessity to import green hydrogen from regions with larger renewable energy resources.[26] In industrial and climate policy terms, this can of course only be seen as complementary to the building up of own green hydrogen capacities.
- Not all technological paths for the production of green hydrogen currently have the requisite market maturity or infrastructure to be cost-competitive. Achieving this on the one hand necessitates further research efforts and, on the other, investments in getting the market up and running in order to achieve economies of scale. This and additional regulatory aspects (e.g. exemption of electrolysis from the REA surcharge, CO2 tax, etc.) will be dealt with later in this study.
- The production of green hydrogen is currently energy-intensive. For example, the substitution of the 70m tonnes of hydrogen currently produced directly worldwide would require a volume of 3,600 TWh of electrical energy from renewable energy sources. This is more than the volume of electricity generated annually in the EU.[27] To put this in relation: the volume in 2018 was 2,806 TWh, of which approx. 29 percent came from renewables.[28] A calculation for Germany indicated that alone the switchover in the country's annual steel production to the use of green hydrogen would make for a 20-percent rise in electricity demand.[29] However, it can be assumed that there will be improvements in energy

[25] McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution, No. 8/2021, April 2021; ATKearney: Hydrogen applications and business models - Going blue and green ?, June 2020; Hydrogen Council: Path to hydrogen competitiveness - A cost perspective, January 2020; IEA: The Future of Hydrogen, sizing today's opportunities, June 2019; DLR: Hydrogen as an element of the energy transition, part 1: Technologies and perspectives for a sustainable and economical hydrogen supply, September 2020; Kemfert: Green and efficient!, in: DIW Wirtschaftsdienst 2020
[26] Various countries in the MENA region (Middle East and North Africa) are already positioning themselves accordingly. These include Morocco and Saudi Arabia.
[27] IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[28] Eurostat: Energy, transport and environment statistics, 2020 edition, 2020
[29] Kurrer: The potential of hydrogen for decarbonizing steel production, EPRS - European Parliamentary Research Service, December 2020

efficiency over time. Nevertheless, there will always be losses in efficiency in the production of green hydrogen or its transformation back into energy.

All in all, it can be said that building a green hydrogen economy constitutes a challenge that ought not to be underestimated. As outlined, this includes the coupling of the development of a hydrogen infrastructure with the expansion of renewable energies, the creation of supraregional and regional transport networks and, if necessary, an initial prioritization of the application areas for green hydrogen. The latter means that, among other things, it may make sense to concentrate on application areas that are difficult to make climate-neutral without hydrogen and/or in which economies of scale can be rapidly achieved.[30]

Despite these challenges, it can already be pointed out at this stage that the topic of a hydrogen economy is clearly gaining momentum. More than 30 countries around the world have put hydrogen roadmaps in place. Moreover, over 200 projects have been announced, 55 percent of which will be in Europe and represent a total investment volume in excess of USD 300bn. Of these, projects with a total volume of USD 80bn and distributed along the entire value chain are at a concrete planning level.[31]

Integration of hydrogen into climate neutrality measures

The above facts and considerations make it clear that hydrogen must be embedded in an overall concept towards achieving climate neutrality. A contributory factor in this context, alongside the aspects already outlined, lies in the fact that the hydrogen economy is to account for a proportion of approx. 13-14 percent of the energy mix in the EU by 2050.[32] Various conclusions can be drawn from this:

- Green hydrogen is a technology that is first and foremost to be used where the direct utilization of renewables is not possible or not economically viable.
- Technologies and areas of application in which renewables without energy-intensive conversion processes are used account for a bigger share of the energy mix.
- However, the scaling up of the two action strands ultimately means a substantially higher demand for energy and electricity of which account must be taken.

Against the background of the latter aspect in particular, the structure of the hydrogen economy therefore needs to be integrated into a four-point set of climate neutrality measures as shown in the following chart. This set of measures comprises:

- Expansion of renewables, in which process the existing, albeit ultimately limitedly available renewable-energy potential is gradually exploited. In this regard it is without doubt more important to invest in communication with the general public.
- Continuous improvement of energy efficiency. This is imperative since the gap between the limited availability of renewable-energy potential on the one hand and, on the other, the competition for their use due to growing demand potential will otherwise increasingly widen. Should this be the case, the risk of having to relocate production capacities to other countries with higher and/or more cost-effective capacities could become virulent. The creation of internationally competitive value chains in Germany would then be made far more difficult as well. A higher degree of energy efficiency in all areas can consequently contribute towards optimizing the energy demand and thus towards narrowing the gap.

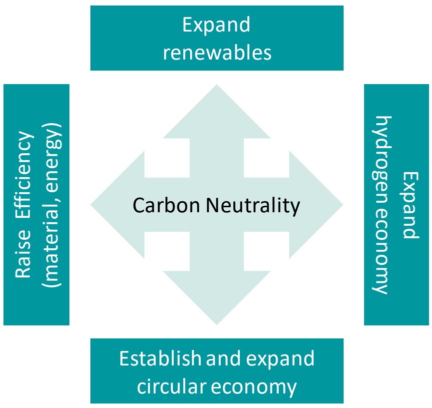
[30] McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution, No. 8/2021, April 2021; Hegnsholt, Klose, Burchardt, Schönberger: The real promise of hydrogen, BCG, July 2019

[31] Hydrogen Council, McKinsey: Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, February 2021

[32] European Commission: A hydrogen strategy for a climate-neutral Europe, July 2020

- Enhancement of material efficiency. Similar reasoning applies here. A reduction in material input enabled by adjustments in product design, the reduction of waste through new manufacturing techniques or the use of alternative materials could possibly facilitate a scaling back of the production of energy-intensive base materials. This would inevitably affect the energy demand. The legislators could also contribute in this respect by revising the Ecodesign Directive. [33]
- Concentrated establishment of a circular economy. This essentially means an enhancement in material efficiency, since the recycling of high-quality base materials can enable the replacement of base materials primarily produced as input for industrial processes. Incidentally, this can also be achieved by taking greater account of the possibilities for repair or reuse in product development. Setting quotas for the use of recycled materials in production processes could accelerate the establishment of a circular economy, too.[34]
- Establishment of a hydrogen economy. This, too, is imperative, since not all areas can be directly made climate neutral by means of renewables. Furthermore, the hydrogen economy is also of importance in terms of industrial policy, as it can provide positive stimuli for coping with structural change in many sectors (e.g. refineries), generate new added value in Germany and contribute to the development and exploitation of new international product/market combinations (e.g. electrolysis plants) in German industry. In this respect its importance thus extends beyond the contribution towards achieving climate neutrality, as will become clear in the following section.

Chart: The four-point set of climate neutrality measures



Source: NORD/LB Sector Strategy

[33] On these aspects, cf. Neuhoff et al: Green Deal for Industry: Clear framework conditions are more important than funding, DIW weekly report, No. 10/2021; AGORA Energiewende, Stiftung 2°, Roland Berger: Climate neutrality 2050: What industry needs from politics now, February 2021

[34] On these aspects, cf. Neuhoff et al: Green Deal for Industry: Clear framework conditions are more important than funding, DIW weekly report, No. 10/2021; AGORA Energiewende, Stiftung 2°, Roland Berger: Climate neutrality 2050: What industry needs from politics now, February 2021

Application areas for green hydrogen

Preliminary note

With the fundamental importance of a hydrogen economy having been emphasized in the above, the following provides a brief outline of selected areas of application. [35]

Applications in the chemical industry

There are two main areas of application within the chemical industry, namely ammonia and methanol production.

- Ammonia is one of the most important base chemicals and is used in the production of fertilizers, urea, nitric acid, explosives, plastics and synthetic fibres. Demand is correspondingly high, as reflected in the fact that approx. 17m tonnes are produced per year in Europe.[36] Germany registered a volume of 3.13m tonnes in 2017 [37]. Against this background it is hardly surprising that, with a global demand of 31m tonnes, the ammonia synthesis process figures among the biggest spheres of hydrogen consumption.[38] There is thus a high potential for substitution by green hydrogen, even if CO2 still has to be admixed in the production of urea, for example.

  The further demand for ammonia will for the time being be determined by the increasing demand for fertilizers owing to the expanding world population. This admittedly only applies to a limited extent where Europe is concerned, since the EU is increasingly placing priority on the use of organic raw materials in fertilizers and, for example, the Fertilizer Ordinance ultimately limits the demand in Germany. A growing demand in the EU for ammonia in this context can therefore be virtually ruled out. That said, ammonia is also a good energy carrier that enables the transport of hydrogen over long distances as well or can be used as fuel. This characteristic could make for a surge in demand for ammonia, though conversion losses must be taken into account.
- Methanol is likewise a key basic chemical, used in the production of solvents, acetic acid and formaldehyde. In addition, methanol can be used as a fuel, as energy supplier for fuel cells or as an input material in the production of biofuels. The production of methanol currently requires an annual volume of hydrogen amounting to 12m tonnes[39] worldwide, which could be substituted with the green variety. Even if new applications for methanol arise as against the status quo (e.g. fuel), the level of demand will remain lower than for ammonia in the future as well.

The chemical industry is thus proving to be a potential driver in the building up and establishment of a green hydrogen infrastructure.

[35] On the following details and information, cf.: McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution, No. 8/2021, April 2021; Hydrogen Council, McKinsey: Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, February 2021; European Commission: A hydrogen strategy for a climate-neutral Europe, July 2020; ATKearney: Hydrogen applications and business models – Going blue and green ?, June 2020; IEA: The Future of Hydrogen, sizing today's opportunities, June 2019; Hebling et al: A Hydrogen Roadmap for Germany, Fraunhofer, October 2019; Fuel Cells and Hydrogen 2 Joint Undertaking: Hydrogen Roadmap Europe, A sustainable pathway for the European energy transition, January 2019; DLR: Hydrogen as a foundation of the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020

[36] McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution No. 08/2021, April 2021

[37] DLR: Hydrogen as a foundation of the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020

[38] IEA: The Future of Hydrogen, sizing today's opportunities, June 2019

[39] IEA: The Future of Hydrogen, sizing today's opportunities, June 2019

Refineries

With a global hydrogen requirement of 38m tonnes, refineries also figure among the biggest consumers.[40] It is used in the context of hydrotreatment and hydrocracking in the processing and refining of crude oil into end products such as fuels or heating oils. In light of the growing degree of electrification of the transport and heating sectors, however, the demand for corresponding petroleum-based end products will likely decline, meaning that less hydrogen (including green hydrogen) would be required for these purposes. A complete decarbonization of fuels and combustibles by 2050 would lead to a massive decline in the demand for hydrogen. [41]

That said, a field of activity will likely open up for the refineries in the production of synthetic fuels or synthetic hydrocarbons.[42] The resultant demand cannot yet be reliably assessed.

Extractive industry

A further area of application for green hydrogen is opening up in the production of base materials, for example cement. This area of application is an important one since the extractive industry accounts for 16 percent of the CO2 emissions in the EU and is crucial for downstream stages of the value chain. Using renewables in the production of such products thus also has a positive effect on the downstream stages. The use of green hydrogen in this area of application arises from the aspect that high-temperature heat is generally required for their manufacture. Indeed, such products can in some cases be better produced with hydrogen than with the direct use of electrical energy. The extractive industry is thus similar to the chemical industry and the steel production sector in this respect.[43]

Steel production

With a global hydrogen consumption volume of 4 tonnes per year, the steel production sector is a further major source of demand. The fact that we can safely assume that the demand for steel will continue to grow[44] means that the demand for hydrogen will also increase. At the same time, however, steel production accounts for approx. 28 percent of the world's CO2 emissions.

Two different methods are currently used to produce steel, namely the BOF method[45] (approx. 60 percent of European steel production) on the one hand and the EAF method[46] (approx. 40 percent of European steel production) on the other.[47] In the first process, iron ore is reduced to pig iron with coke and the residual carbon is subsequently blown out with oxygen. A reduction in CO2 could be achieved here by partially replacing coke with green hydrogen. In addition, oxygen from the water electrolysis process could be used to blow out the residual carbon. However, it is also evident from this that a residual amount of CO2 is left. However, this could be separated and processed with green hydrogen into synthetic fuels or chemical base materials.

The EAF method, on the other hand, involves the use of electrical energy, which makes for a significant reduction in CO2 emissions (approx. 70-75 percent) compared to blast furnaces.

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[40]IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[41]AGORA Energiewende, AFRY Management Consulting: No-regret hydrogen: Charting early steps for H2 infrastructure in Europe, February 2021
[42]IG BCE: Secure industrial sites and convert them to be climate-friendly. The perspective of IG BCE, December 2020; Hebling et al: A hydrogen roadmap for Germany, Fraunhofer, October 2019
[43]IEA: The Future of Hydrogen, sizing today's opportunities, June 2019; Neuhoff et al: Green Deal for Industry: Clear framework conditions are more important than funding, DIW weekly report No. 10/2021
[44]The IEA expects annual growth of 6 percent through to 2030. IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[45]BOF = Blast Oxygen Furnaces
[46]EAF = Electric Arc Furnaces
[47]McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution No. 8/2021, April 2021

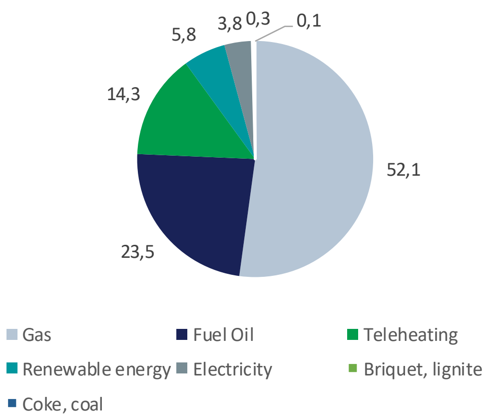
Steel scrap or sponge iron from the direct reduction process (DRI) can be used as raw material for this purpose. The former contributes towards the circular economy's realization but is not sufficiently available as yet. DRI still plays a subordinate role, but can use green hydrogen directly to produce sponge iron from iron ore. Overall, there is a tendency in Europe towards the use of the EAF method, though the DRI method will likely gain in importance in the future.

Given that what will in many cases be major investments with a long utilization and amortization period (approx. 35 years) are to be expected by 2030 – as is the case in the chemical industry – we should already now be looking to put the framework conditions in place. [48]

Heating (buildings)

According to the Federal Statistical Office (Destatis), there were over 19 million residential buildings in Germany in 2018, 83 per cent of which being single-family and two-family houses. The remaining 17 percent are accounted for by multi-family houses. The dwellings are predominantly heated with gas, as the following chart shows.

Chart: Types of energy for heating dwellings in Germany, 2018 (in %)



Source: NORD/LB Sector Strategy

The greatest potential for decarbonizing housing is seen in electricity-based solutions, such as, above all, electrically operated heat pumps. This is largely due to the fact that renewables can be used for this purpose without the necessity for further conversion processes. Solutions of this nature are therefore more energy-efficient than those involving hydrogen. These considerations are augmented by, above all, the requirements on new-builds and renovations, which are intended to ensure significantly reduced energy consumption.[49]

This of course does not mean that green hydrogen cannot be used. Its possible applications are envisaged primarily in office buildings or building complexes with the use of fuel cell cogeneration plants. Solutions and pilot projects already exist for single-family houses as well, but these require a corresponding hydrogen supply (e.g. via pipelines).[50] They can possibly be used in the old building stock, which is sometimes hardly suitable for the use of heat pumps. Hydrogen can, of course, also be added into to the existing gas network, but this as a rule requires investments in the grid and would have comparatively minor effects in terms of climate neutrality.

[48] Agora Energiewende, Stiftung2°, Roland Berger: Climate neutrality 2050: What industry needs from politics now, February 2021
[49] Cf., inter alia, the EU 2020 Renovation Wave Strategy
[50] Cf. DLR: Hydrogen as a foundation for the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020; Wetzel, Fabricius: Bosch distrusts the heat pump hype – and pushes the hydrogen idea, www.welt.de/228674935, 19.3.2021

Green hydrogen is therefore not attributed any great market potential at the current time as regards heat supply for residential buildings.

Transport sector

Promising spheres of application for green hydrogen are seen in the largely petrol and diesel fuel-based transport sector, too. These lie in substituting the currently used fuels with hydrogen and its involvement in the production of synthetic fuels. The extent of the potential, however, depends on the underlying conditions in the various transport segments, for which reason these are examined individually in the following.

- **Road transport:** In this segment the hydrogen technologies have all-electric battery power as competition. But first the following *a priori* considerations in this regard: BEVs (vehicles with battery-electric drives) boast the highest energy efficiency (well to wheel[51]) since there are no conversion losses involved. However, batteries have a lower energy density per kg (0.6 MJ/kg), making them particularly suitable for lighter cars and shorter distances. A further disadvantage lies in the comparatively long time required for recharging. Fuel cells (hydrogen), on the other hand, are characterized by a significantly higher energy density per kg (2.6 MJ/kg) and shorter refuelling times, as well as a long range (similar to conventional fuels). The disadvantage, however, lies in the fact that their well-to-wheel energy efficiency is around 30 percent lower. This technology is thus more suitable for travel over long distances and vehicles with a high required load capacity.[52]

  Against this background it can be concluded that the all-electric battery drive will have particular advantages in the sphere of **private car transport**. Exceptions are given where cars are driven a lot and over long distances. With a required range of 400 km, we could see cost parity between fuel cells and all-electric drives in around 2030. The fuel cell could also have comparative advantages for cars in commercial operation (e.g. taxis).[53] Overall, the proportion of fuel cell-driven vehicles is put at between 10 and 20 to 25 percent, depending on category.[54] This assertion, however, should not obscure the fact that the fuel cell technology is being massively fostered and subsidized (between 2021 and 2024 with USD 5bn[55]) in a number of countries, such as China, and that Asian OEMs in particular are working on the technology.

  In principle, the assertions regarding taxi fleets apply analogously in **local public transport**. Buses operating in rural areas and urban centres have considerable requirements in terms of range. Fuel cell-driven buses can be operated for up to 18 hours a day.[56] Hydrogen thus has comparative advantages[57]in this area of application, even if in the end – as in the case of cars – the electric and hydrogen propulsion technologies will be in operation alongside each other. The acquisition of the two technologies is also given support by the EU's Clean Vehicle Directive from 2019, which lays down that 45 percent of new busses purchased under public procurement tenders between 2021 and 2025 must run on clean technologies. This quota will then rise to 65 percent between 2026 and 2030. All in all, therefore, the hydrogen technology can well be expected to have sound prospects of growing market shares in this segment.

[51]well to wheel = efficiency of energy supply plus vehicle efficiency

[52]Hydrogen Council: Hydrogen scaling up – A sustainable pathway for the global energy transition, November 2017; DLR: Hydrogen as a foundation for the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020

[53]Hydrogen Council: Path to hydrogen competitiveness – A cost perspective, January 2020.

[54]Hydrogen Council: Hydrogen scaling up - A sustainable pathway for the global energy transition, November 2017

[55]Hydrogen Council, McKinsey: Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, February 2021

[56]DLR: Hydrogen as a foundation of the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020

[57]This also applies to coaches, which have to combine a corresponding load with high range requirements.

In **road-based freight transport** a distinction must in turn be made between **light** and **heavy-haul transport**. The assertions on taxi fleets apply analogously for light-haul transport vehicles, even if a possible long range without refuelling promises advantages and good market opportunities for the use of hydrogen. Where heavy-haul transport is concerned, fuel cell technology has distinct advantages in terms of vehicle design and structure, so it will very likely gain the upper hand over the all-electric alternative. (As in the other segments, the prerequisite is, of course, the development of a nationwide network of hydrogen filling stations). With this in mind, a large number of truck manufacturers are already working on corresponding solutions. OEMs in the Asian region appear to be at the head of the field in this case, too, as reflected in the fact that, for example, Bosch is already working with Chinese firms on a fuel cell system in the interests of opening up this key market.[58]

- **Rail transport:** 53.9 percent of Germany's rail network had been electrified by 2015.[59] There is no point in using hydrogen-powered trains on these lines, irrespective of whether in passenger or freight transport, since that would involve conversion losses. That said, 46.1 percent of the lines are not electrified, so there is potential for replacing diesel-powered trains with trains fuelled with hydrogen. This applies in particular to local rail passenger transport which, by virtue of its timetable-based operation, guarantees a stable demand for hydrogen and thus good capacity utilization of facilities for the storage, processing and refuelling of hydrogen.[60] In Lower Saxony, the mobility solutions provider Alstom has developed and built Coradia iLint, the world's first fuel cell-driven train; this is already in action on test tracks. Over the next 20 years we can expect an overall demand for fuel cell-driven trains in the mid to high three-digit range in Germany. It should also be borne in mind that trains of this type have a not inconsiderable market potential in terms of export as well. Taken as a whole, this segment is rather small but could be interesting from an export point of view, however.
- **Water-borne transport:** The environmental impact of fossil fuels, especially heavy fuel oil, has long been a topic of discussion in the sphere of water-borne transport, against which background the replacement of fossil fuels is a logical consideration. Fuel cells are capable of being an alternative for use on passenger ships (river boats, cruise ships) or ferries, especially since correspondingly powered ships are already in use. However, synthetic fuels based on renewables or hydrogen converted into methanol or ammonia as fuel for combustion are considered to have greater potential. Before technologies of this type can really make an impression on the market, however, it is first essential to ensure the availability of corresponding infrastructure in the ports.
- **Air transport:** Despite the low single-digit share of global CO2 emissions for which it accounts, the starting situation in the area of air transport is similar to that of water-borne transport. Here, too, decarbonization would send a clear signal. Accordingly, Airbus, for example, has developed three concepts that are to be pursued, evaluated and developed to market maturity by 2035.[61]

  There are in principle three alternatives available as substitute for kerosene, as described in the following:[62]

[58] Preuss: Bosch now aims to penetrate the China market with the fuel cell, www.faz.net, February 14, 2021
[59] DeStatis
[60] DLR: Hydrogen as a foundation of the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020
[61] Airbus: ZEROe: reducing the climate impact of flying, presentation
[62] DLR: Hydrogen as a foundation of the energy transition, part 2: Sector coupling and hydrogen: two sides of the same coin, September 2020

- Hydrogen converted into synthetic fuels. This would have the advantage that the drive technology currently in use would only need very little adaptation. On the other hand, the low degree of conversion efficiency would be a disadvantage. The market potential for this is seen primarily in long-haul routes.
- The direct use of hydrogen as fuel in a gas turbine. The advantage would lie in the high power density of hydrogen; this would be of particular interest for wide-body aircraft. However, the development of hydrogen storage systems suitable for use in aviation still has a long way to go and, due to the problem of nitrogen emissions, new combustion chamber systems are an essential requirement.
- Flying with fuel cells and electric drives. This approach, too, involves complex technical challenges but would deliver quiet, efficient and emission-free propulsion systems. Recent studies and simulations show that aircraft with a propulsion system of this type can be realized with a capacity of up to 160 passengers and a range of 2,500 kilometres. The fact that such flights account for around 60 percent of aviation-induced CO2 emissions makes the fuel cell a serious alternative in air transport.

Summary

All in all, it becomes clear that there are many application areas for green hydrogen, though not all of them are ready for the market. Moreover, they differ – as the following chart shows – in terms of their demand potential. It is not yet possible to estimate this demand potential with sufficient accuracy, with Bruegel, a think tank, estimating levels of demand in Europe in the respective application areas ranging between 0 and 300 TWh.[63] In industrial applications in particular, however, the lower demand limit is greater than zero.

Chart: Application areas and potential demand for green hydrogen

Field of application	Potential demand
Chemical industry	very high
Extractive industry	very high
Steel production	very high
Refineries	low to medium
Heating (buildings)	more low
Car Private	low
Car Commercial	low to medium
Ligh Four-Wheeled Vehicle	low to medium
Heavy Goods Vehicle	low to medium
Bus	low to medium
Water-borne transport	low to medium
Air transport	low to medium

Sources: Bruegel, IEA, NORD/LB Sector Strategy

[63]McWilliams, Zachmann: Navigating through hydrogen, Bruegel Policy Contribution No. 8/2021, April 2021

Hydrogen strategies: EU and Germany

Preliminary note

The facts and considerations set out in the above have shown that a hydrogen economy has a great deal of potential in terms of applications for the technology. Correspondingly, its implementation and development are also associated with considerable economic aspects. The Fuel Cells and Hydrogen 2 Joint Undertaking quantifies these as follows for European companies:[64]

- Achieved sales volume hydrogen, plants/systems, etc. 2030: EUR 130bn, of which 70bn from export sales
- Achieved sales volume hydrogen, plants/systems etc. 2050: EUR 830bn

The associated employment effects are estimated at 1m new jobs by 2030 and 5.4m by 2050. These figures should certainly be used with some caution since the levels of demand are still uncertain, the hydrogen economy's costs are not yet competitive, and the estimated employment effects in our view lie more in the plant/facilities sector (construction of electrolysis plants, fuel cells, supply infrastructure facilities, etc.) and less in the actual deployment of hydrogen.

All the same, there will be positive economic effects, which – and these figures justifiably make this clear – will likely not manifest themselves in any greater dimension until beyond 2030. This is ultimately due to the fact that many of the applications could – provided the market development proves positive – achieve their cost competitiveness against existing technologies from 2030 onwards.[65] Accordingly, the IEA also emphasized in 2019 that the next 10 years will be decisive for the successful establishment of a sustainable hydrogen economy.[66] This applies particularly in light of the necessity for considerable investments in infrastructure. It goes without saying that these will only be made against a background of adequate security of investment. That said, projects with a total global volume of approx. USD 300bn have already been announced, USD 80bn of which relate to projects that are already at an advanced stage of planning.[67]

The following aspects must nevertheless be taken into account so that the complex interdependencies between the growing and competing demand for renewable energies, a competitive hydrogen offering, political policy, technological innovations in hydrogen applications and demand preferences work together towards the development of an integrated, sustainable hydrogen economy. The aspects include, among others:

- Significant expansion of the renewables. According to AGORA Energiewende, the annual growth in solar and wind energy will have to have doubled by 2030. This means that, instead of the 76 gigawatts planned up to now, 140 gigawatts of new capacity would have to be installed in order to achieve the climate targets.[68]
- Development of hydrogen production capacities (supply side) so that by 2030 the costs of currently approx. USD 5.4/kg to 6/kg will drop to between USD 1.4/kg and 2.3/kg.[69] As already outlined above, the establishment of an international, respectively European

[64] Fuel Cells and Hydrogen 2 joint Undertaking: Hydrogen Roadmap Europe – A sustainable pathway for the European energy transition, January 2019
[65] Hydrogen Council, McKinsey: Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness, February 2021
[66] IEA: The Future of Hydrogen, sizing today's opportunities, June 2019
[67] Hydrogen Council, McKinsey: Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness, February 2021
[68] Agora Energiewende, Stiftung2°, Roland Berger: Climate neutrality 2050: What industry needs from politics now, February 2021
[69] Hydrogen Council, McKinsey: Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness, February 2021

hydrogen economy, including a transport network within and extending beyond Europe, is of crucial importance towards ensuring the supply of green hydrogen.

- Support of the production ramp-up by way of regulatory aspects, such as adequate CO2 taxation[70], CO2 differential contracts to reduce investment uncertainties, an exemption for electrolysis from the Renewable Energies Act levy[71], and the like.[72]
- Acceleration of the development and market readiness of technologies in the various areas of hydrogen application. We regard this as imperative towards the establishment and scaling up of national value chains which also open up export opportunities for German industry as well. This expansion of demand must in our view largely take place in parallel with the expansion of the supply side, so that the potential can be made clear and a level playing field is created. This is essential for the establishment of successful business models in a hydrogen economy and thus of job-creating value chains. Moreover, it makes no economic sense to build up supply capacities for which there is no demand.

It is immediately understandable that the state institutions play a central role in this, so that the investment risks can initially be covered. This has also been essentially recognized and integrated into various hydrogen strategies, examples of these are briefly in the following.

Hydrogen Strategy, EU[73]

- Objective:

  Development and establishment of a sustainable hydrogen economy and competitive industrial structures across all stages of the value chain. This includes the creation of a level playing field for successful hydrogen business models. This strategy is to be seen in the context of the European Green Deal and the New Industrial Strategy for Europe.
- Supply side:

  Development takes place in three phases with the objective of reducing electrolysis costs by 50 percent through the achievement of economies of scale.

  At least 6 GW of green hydrogen electrolysers are to be installed between 2020 and 2024 for the production of up to 1m tonnes of green hydrogen. At the same time it is planned to develop the industrial production of electrolysis plants capable of producing up to 100 MW and which are initially intended to support the industrial processes. This is important because Europe might otherwise find itself lagging behind other regions such as China, for example.

  In a second phase between 2025 and 2030, plants with a volume of at least 40 GW for the production of up to 10m tonnes of green hydrogen are to be installed. This is to be supplemented by a further 40 GW in neighbouring regions, as the EU is aware of the limited availability of renewables and the cost advantages that, for example, hydrogen production in North Africa has. Combined with this, the strategy naturally also provides for investments to be made in hydrogen applications, storage capacities, transport capacities and other infrastructure. In this context the EU attaches great importance to local hydrogen clusters.

[70] In this regard, many experts recommend reforming the EU ETS in the direction of expanding its application and increasing CO2 prices.
[71] This is part of the REA amendment 2021
[72] Agora Energiewende, Stiftung2°, Roland Berger: Climate neutrality 2050: What industry needs from politics now, February 2021
[73] European Commission: A hydrogen strategy for a climate-neutral Europe, July 2020

- Demand side:

  In the third phase, all major hydrogen application areas are to be well ready for the market and be competitive due to the economies of scale. In particular it is to be ensured all application areas that cannot be decarbonized without green hydrogen have sufficient hydrogen at their disposal and will be able to function economically. The further expansion of renewables must take place in parallel to this.
- Import of green hydrogen:

  The import of green hydrogen is an implicit element of the strategy and is to be realized through the development and building up of electrolysis capacities in neighbouring regions such as North Africa, for example.
- Estimation of needed investments:

  The implementation of all three phases naturally requires corresponding investments, for which purpose, the EU is making available both its various funding programmes as well as the instruments of the European Investment Bank. Overall, the EU estimates the investments needed as follows:
  - Build-up of electrolysis capacities: between EUR 24bn and EUR 42bn by 2030; by 2050 the investments will total between EUR 180bn and 470bn.
  - Expansion of renewables for direct use in electrolysis plants (approx. 80 to 120 GW): by 2030 between EUR 220bn and 340bn.
  - Conversion of existing industrial plants to the use of blue hydrogen as bridging technology: around EUR 11bn.
  - Development of a hydrogen infrastructure (transport, storage, distribution): around EUR 65bn.
  - The EU also envisages considerable investments in the application areas, though these are not quantified in detail.
- Additional aspects/measures:

  Additionally to the above, the development of the various application areas is to be supported by the introduction of hydrogen quotas and EU-wide criteria for the certification of green hydrogen products. Emissions trading, too, is to make its contribution towards establishing a sustainable hydrogen economy, even if the current CO2 prices are viewed by many experts as too low.

In the aggregate, the EU strategy is thus set to begin with a holistic development of a hydrogen economy, with the focus initially on building up production capacities.

Hydrogen Strategy, Germany[74]

Germany, too, has adopted a hydrogen strategy that is similar to the European one in terms of objectives.

- Objective:

  Development of a competitive domestic market for the hydrogen economy. This includes both the supply and the demand side.
- Supply side:

  The strategy currently envisages the construction of electrolysers with a total capacity of up to 5 GW by 2030. This equates to a hydrogen production volume of up to 14 TWh. Subsequently, it is planned add a further 5 GW by 2040 at the latest. This goes hand in hand with the further expansion of the renewables. There are by all means experts who

[74]The Federal Government: The National Hydrogen Strategy, 2020

regard this order of magnitude as not overly ambitious, seeing as fresh domestic capacities are essential for the development and establishment of value chains. In this context it should however be pointed out that the German government, too, first intends to create the conditions for a market ramp-up of the hydrogen economy by 2030.

- Import of green hydrogen:

  The import of green hydrogen is an integral element of the strategy and led to, among other things, the agreements on cooperation with Morocco.

- Demand side:

  Germany, too, intends to support all stages of the value chain and the associated application areas in such a way that the country can take on a pioneering role in Europe. The focus in this context is initially on the industrial use of hydrogen since economies of scale can be achieved there more rapidly. In addition to that, the other application areas are to be developed and supported so that market maturity can be achieved and their successful establishment in international markets can come about. The hydrogen strategy sets out 38 measures for implementation. These include, among others:

  - The "HyLand – hydrogen regions in Germany" funding measure as an approach to supporting the creation, refinement and implementation of integrated regional hydrogen concepts.
  - Development and funding of plants for the production of electricity-based fuels. The funding will be provided from the Energy and Climate Fund until 2023.
  - The coordinated development of a needs-based fuelling infrastructure. For this, too, funding will be available from the Energy and Climate Fund until 2023.
  - Establishment of a competitive supply industry for fuel cell systems. This is a key aspect, especially from the perspective of creating competitive value chains.

- Additional aspects/measures:

  - An international harmonization of standards concerning mobility applications for hydrogen and fuel cell systems.
  - A pilot project entitled Carbon Contracts of Difference, which is primarily aimed at the steel and chemical industries and for the purposes of guaranteeing the security of the upcoming investments in view of the long investment horizon involved.
  - Strong support for hydrogen-oriented research within the framework of the “Hydrogen Technologies 2030” initiative. An important part of this initiative lies in "living labs" set up to stimulate innovation in the energy transition, for which funding of EUR 600m is available until 2023.
  - Having come into effect on 1 January 2021, the amendment to the Renewable Energies Act (REA) includes the exemption of electrolysis systems from the REA levy provided they are operated with renewable energies. This improves the cost-effectiveness of electrolysis systems since a central cost driver (costs of renewables) becomes less important.
  - From 2021 onwards, CO2 prices will be introduced for the spheres of heating and transport. Even if these are comparatively low at EUR 25 per tonne CO2 in the first step, this step will help create a level playing field. This also applies against the background that the CO2 price is to increase gradually to EUR 55 per tonne CO2 by 2025 and subsequently level off between a minimum of EUR 55 and a maximum of EUR 65 per tonne CO2.

- Within the framework of the government's corona recovery stimulus package an amount of EUR 7bn has been earmarked for development of hydrogen technologies and applications and EUR 2 billion for forging international partnerships.

All in all, there is a broad framework here that ought to enable the development of a hydrogen economy in Germany. In the interests of the further market ramp-up of a green hydrogen economy, it would be in our view be essential that considerations should already be given to a follow-up for the support and funding programmes that expire in 2024 and, where necessary, that the comparatively fragmented funding programmes are more closely integrated with the focus on the hydrogen economy.

Conclusion: Green hydrogen on the advance – but prudent deployment is called for

In summary, it can be concluded that the development and establishment of a green hydrogen economy is a key, integrated building block in addressing the challenge of climate change. It can also be concluded that the implementation thereof has gained significant momentum. The stimuli behind this come both from the political policymakers – as illustrated by the hydrogen strategies – as well as from industry – as illustrated by many projects. Against this background it can safely be assumed that a large number of applications – as the Hydrogen Council shows in a study – can achieve cost parity with the conventional technologies earlier (specifically: from 2030 onwards) than previously estimated. But even if there are delays in this regard, the green hydrogen economy appears to be developing rapidly. It goes without saying that this also involves investments that can have a positive effect on the development of a supplier industry.

Nevertheless, there are in our view still a few comments to be made with regard to the development and expansion of a green hydrogen economy from a climate and industrial policy point of view. This also applies in view of the many uncertainties regarding the development on the demand side. These comments are as follows:

- The establishment of a green hydrogen economy must go hand in hand with a significant expansion of the renewables.
- From the perspective of added value and jobs, priority should be given to the development of a domestic hydrogen economy. At the same time, a significant shortfall in green hydrogen supply coverage is to be expected in the medium term. This shortfall will also be of a permanent nature, albeit probably to a somewhat lesser extent. This makes the creation of import structures a necessity as well.
- Since renewables are only available to a limited extent even with further expansion, green hydrogen should initially be used primarily in those application areas in which decarbonizing is not or hardly possible without hydrogen. In other respects, the direct use of renewables should be a foreground consideration since efficiency losses in the conversion of energy into hydrogen and vice versa can thus be avoided.
- In our view, this prioritization for the time being speaks in favour of using hydrogen in industrial production applications (chemicals, base materials, steel) – this also in light of the fact that there is a particularly high degree of investment potential in these areas, with a pending investment volume of approx. EUR 30bn in the period up to 2025.[75] Since these investments also go hand in hand with a long useful life and a long amortization period, supportive regulatory framework conditions need to be created towards minimizing investment uncertainty.
- As we see it, the essential regulatory framework conditions lie in: adequate CO2 prices and an expansion of the EU ETS, the rapid introduction of Carbon Contracts of Difference and CO2 product requirements. At least the latter must of course be applied to imported products as well so that a risk of carbon leakage can be avoided.[76] Moreover, the public procurement processes should support such transformations as well.

[75]Neuhoff et al: Green Deal for Industry: Clear framework conditions are more important than funding, DIW weekly report No. 10/2021
[76]Neuhoff et al: Green Deal for Industry: Clear framework conditions are more important than funding, DIW weekly report No. 10/2021

- We regard the concept of industry-oriented regional hydrogen hubs as a suitable instrument for the rapid realization of economies of scale.
- In terms of industrial policy, however, the other areas of application should, needless to say, not be lost sight of either since these open up opportunities for the export economy. Against this background, our view is that the various "living labs" set up to stimulate innovation in the energy transition are, insofar as they are also hydrogen-oriented, of crucial importance. Particularly by way of decentralized projects involving, for example, the development of an electrolysis system to supply public transport (buses or rail transport) or the supermarket delivery traffic with green hydrogen based on available resources, further important contributions to the building up and establishment of a green hydrogen economy can be made. This applies in particular to and through locations that do not have the prerequisites an industrial hydrogen hub requires.

All in all, it thus becomes clear that establishing a sustainable hydrogen economy is a challenging mission but, ultimately, without alternative. A good many measures are already under way. What is most important now is to pursue this path systematically in terms of climate and industrial policy – while taking account of the limits of a hydrogen economy – and to steer it prudently along the lines of the above considerations.

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